Exhibit 15

A Novel Concept: Message Driven Frequency Hopping (MDFH)

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Abstract—**Frequency hopping systems have been widely used in military communications to prevent hostile jamming, interception and detection. In traditional frequency hopping (FH) systems, hopping frequency selection at the transmitter end is controlled by a pseudo-random code sequence, and the receiver operates accordingly in exact synchronization with the transmitters hopping pattern. In an effort to meet the ever increasing requirement on information capacity and reduce the burden of synchronization, in this paper, an innovative message-driven frequency hopping (MDFH) system is proposed. By embedding part of information into the process of hopping frequency selection, the spectral efficiency of the FH system can be significantly improved. Quantitative analysis on the proposed scheme is presented to demonstrate its superior performance and enhanced security features.**

I. INTRODUCTION

As one of the two basic modulation techniques used in spread spectrum communications [1], frequency hopping technique was originally designed to be inherently secure and reliable under adverse battle conditions for military purpose. In a conventional FH system, the transmitter "hops" in a pseudo-random manner among available frequencies according to a pre-specified algorithm, the receiver then operates in synchronization with the transmitter and remains tuned to the same center frequency.

Based on the hopping duration, FH systems can be further divided into two categories: fast hopping (FFH) scheme and slow hopping (SFH) scheme. In an FFH system, the carrier frequency will change or hop several times during the transmission of one symbol, while in an SFH system, several symbols are transmitted during each hop. Since it is unlikely that different bands experience simultaneous fading, FH systems are robust against fast fading. At the same time, the pseudo-random hopping of frequencies during radio transmission minimizes the possibility of hostile jamming and unauthorized interception.

In 1978, Cooper and Nettleton [2] first proposed a frequency hopping multiple access (FHMA) system with differential phase shift-keyed (DPSK) signaling for mobile communication applications. Later in the same year, Viterbi [3] initiated the use of MFSK for low-rate multiple access mobile satellite systems. Since it enables non-coherent detection, MFSK modulation has been widely adopted in FHMA systems [4]–[7]. However, along with development on high rate wireless multimedia communications, there has been an ever increasing demand on transmitting more information without extra bandwidth. To improve the information capacity of FHMA systems, consid-erable efforts have been devoted to applying high-dimensional modulation schemes to the FH systems [8], [9]. To the best of our knowledge, to increase spectral efficiency through smart hopping has rarely been taken into consideration.

In this paper, we propose a highly bandwidth-efficient message-driven frequency hopping (MDFH) scheme, for which the selection of carrier frequencies is directly controlled by the (encrypted) message stream rather than by a predetermined pseudo-random sequence as in the conventional FH systems. Note that in today's FH systems, synchronization is the major issue, and the frequency hopping rate is mainly determined by the frequency agility of receiver synthesizers. However, due to advances in digital signal processing and chip manufacturing, it is feasible to capture the transmitting frequency using a filter bank as in the FSK receiver design rather than using the frequency synthesizer. As a result, the carrier frequency can be blindly detected at each hop, and frequency synchronization is no longer required at the receiver end. Hence, MDFH enables faster frequency hopping in wide band systems. Moreover, to resolve collisions in multiple access frequency hopping systems, we incorporate the TDMA architecture as the basic layer of the MDFH transmission scheme, and propose a contention-free TD-MDFH system.

Quantitative analysis is demonstrated that in MDFH, by embedding part of information into the process of hopping frequency selection, the spectral efficiency of the FH system can be significantly improved. At the same time, from the security point of view, information confidentiality is reinforced since the hopping pattern is message-driven, hence totally unpredictable.

II. CHALLENGES IN THE TRANSCEIVER DESIGN OF FREQUENCY HOPPING SYSTEMS

The block diagram of a traditional FH system is shown in Fig. 1. A main limitation with this design structure is
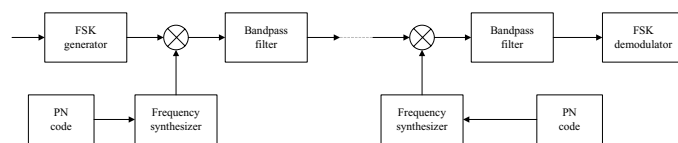

Fig. 1.   The block diagram of the conventional frequency hopping scheme

the strong requirement on PN acquisition, as exact frequency synchronization has to be kept between transmitter and receiver.

Synchronization dominates the complexity and the performance of the system [10]. Slow hopping systems, therefore, have been popular due to their relaxed synchronization requirement. On the other hand, due to their resistance to hostile jamming and interception, fast hopping systems are highly desired in classified information transmission. This raises a big challenge in transmitter and receiver design. In addition to strict synchronization requirement, traditional frequency hopping systems are also being challenged to transport more information with little or no increase in allocated bandwidth. Meeting these challenges requires advanced signaling techniques.

In this paper, we introduce the concept of message-driven frequency hopping (MDFH). The basic idea is that part of the message will be acting as the PN sequence for carrier frequency selection. Taking the original modulation technique (such as FSK or PSK) into consideration, transmission of information through frequency control in fact adds another dimension to existing constellations and the resulting coding gain increases the spectral efficiency significantly. At the same time, the receiver is designed to be able to detect the transmission frequency automatically, hence relaxes the burden on PN acquisition.

In the following sections, we start with single user MDFH and then extend it to the multiple user case. In multiple access environment, the TDMA infrastructure is integrated with MDFH to achieve collision-free multiple access.

III. SINGLE USER MESSAGE-DRIVEN FREQUENCY HOPPING SCHEME

A. Transmitter Design

Let N_c be the total number of available channels, with $\{f_0, f_1, \cdots, f_{N_c-1}\}$ being the set of all available carrier frequencies. Note that all the available channels should be involved in the hop selection, as is required by current frequency hopping specifications (e.g., Bluetooth). The necessary number of bits to specify one channel is given by

$$B_c = \lfloor \log_2 N_c \rfloor. \qquad (1)$$

where $\lfloor x \rfloor$ denotes that largest integer less than or equal to x. If N_c is a power of 2, then each channel can be uniquely represented by B_c bits. Otherwise, ith channel will be associated with the binary representation of the channel index, i mod 2^{B_c}, for $i = 0, \cdots, N_c - 1$, that is, when N_c is not a power of 2, we will allow some B_c-bit strings to be mapped to more than one channels. In the following, for simplicity of notation, we assume that $N_c = 2^{B_c}$.

Let M denote the size of the selected constellation Ω, then each symbol in the constellation represents $B_s = \log_2 M$ bits. Let T_s and T_h denote the symbol period and the hop duration, respectively. $\frac{T_s}{T_h}$, denoted by N_h, represents the number of hops per symbol, and is assumed to be an integer larger or equal to 1. In other words, we focus on fast hopping systems.

At the first step, we divide the data stream into blocks of length $L = N_h B_c + B_s$. Denote the nth block by X_n. Each block consists of $N_h B_c$ *carrier bits* and B_s *ordinary bits*. The *carrier bits* are used to determine the hopping frequencies, and
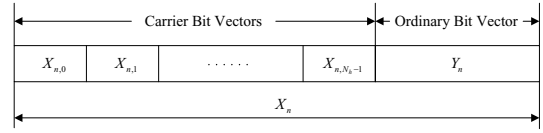

Fig. 2.   The nth block of the information data.

the *ordinary bits* are mapped to a symbol in the constellation Ω and transmitted through the selected channels. Each block is designed to be transmitted within one symbol period. Note that the number of the carrier bits is determined by B_c (the number of bits used to specify a hopping frequency) and N_h (the number of hops within one symbol period). For frequency selection, the carrier bits in block X_n are grouped into N_h vectors of length B_c, denoted as $\{X_{n,0}, \cdots, X_{n,N_h-1}\}$. The bit vector composed of B_s ordinary bits, is denoted by Y_n, as shown in Fig. 2.
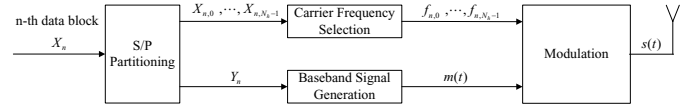

Fig. 3.   Block diagram of the transmitter design.

The transmitter block diagram of the proposed MDFH scheme is illustrated in Fig. 3. Each input data block, X_n, is fed into a serial-to-parallel converter, where the carrier bits and the ordinary bits are split into two parallel data streams. The selected carrier frequencies corresponding to the nth block are denoted by $\{f_{n,0}, \cdots, f_{n,N_h-1}\}$, where each $f_{n,i} \in \{f_0, f_1, \cdots, f_{N_c-1}\}, \forall i \in [0, N_h - 1]$. Assume Y_n is mapped to symbol A_n, and we denote the baseband signal generated from the ordinary bits by $m(t)$.

If PAM modulation is adopted for baseband signal generation,

$$m(t) = \sum_{n=-\infty}^{\infty} \sum_{i=0}^{N_c-1} A_n \, g(t - nT_s + iT_h), \qquad (2)$$

where $g(t)$ is the pulse-shaping filter. Multiplying $m(t)$ with carrier signals generates the bandpass waveform, given by

$$s(t) = \sqrt{\frac{2}{T_h}} Re\{ \sum_{n=-\infty}^{\infty} \sum_{i=0}^{N_c-1} m(t) e^{j2\pi f_{n,i}t} \chi_{n,i}(t)\} \qquad (3)$$

where

$$\chi_{n,i}(t) = \begin{cases} 1, & t \in [nT_s + iT_h, nT_s + (i+1)T_h], \\ 0, & otherwise. \end{cases} \qquad (4)$$

If MFSK is utilized for baseband modulation,

$$s(t) = \sqrt{\frac{2}{T_h}} \sum_{n=-\infty}^{\infty} \sum_{i=0}^{N_c-1} cos2\pi(f_{n,i}t + K_f \int_{-\infty}^{t} m(\tau)d\tau)\chi_{n,i}(t). \qquad (5)$$

where $m(t)$ is a piecewise constant function, i.e., it is a constant over each block period, determined by the MFSK modulation.

B. Receiver Design

The structure of the receiver is shown in Fig. 4. Recall that $\{f_0, f_1, \cdots, f_{N_c-1}\}$ is the set of all available carrier frequencies. Supported by advances in energy-efficient signal processing and chip manufacturing, a bank of N_c bandpass filters (BPF), each centered at f_i ($i = 0, 1, \cdots, N_c - 1$), and with the same channel bandwidth as the transmitter, is deployed simultaneously at the receiver's front end. In the single user case, since only one frequency band is occupied at any given time instant, we simply measure the outputs of bandpass filters at each possible signaling frequency, the actual carrier frequency at a certain hopping period can then be detected by selecting the one that captures the strongest signal. As a result, blind detection of the carrier frequency is achieved at the receiver end.
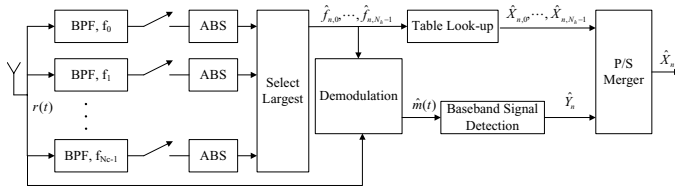

Fig. 4. Block diagram of the receiver design, where ABS means taking the absolute value.

More specifically, the received signal can be written as

$$r(t) = h(t) * s(t) + w(t), \tag{6}$$

where $*$ stands for convolution, $h(t)$ is the channel impulse response, and $w(t)$ denotes additive Gaussian noise. Accordingly, the outputs of bandpass filters are given by

$$z_i(t) = q_i(t) * r(t), \quad \text{for i} = 0, \cdots, N_c - 1, \tag{7}$$

where $q_i(t)$ is the ideal bandpass filter centered at frequency f_i, $i = 0, 1, \cdots, N_c - 1$.

If the channel is ideal, i.e., $h(t) = \delta(t)$, then

$$z_i(t) = s(t) + u_i(t), \quad \text{for i} = 0, \cdots, N_c - 1, \tag{8}$$

where $u_i(t) = q_i(t) * n(t)$ is the filtered noise. If the signal-to-noise ratio is sufficiently high, as in most useful communication systems, there is one and only one significantly stronger signal among the filter bank outputs.

The estimated hopping frequencies $\{\hat{f}_{n,0}, \cdots, \hat{f}_{n,N_h-1}\}$ are used for the reception of the baseband signal $m(t)$, to obtain the estimated ordinary bit-vector $\hat{Y}_n$. At the same time, $\{\hat{f}_{n,0}, \cdots, \hat{f}_{n,N_h-1}\}$ are mapped back to B_c-bit strings to recover the carrier bits. Denote the estimated version by $\{\hat{X}_{n,0}, \cdots, \hat{X}_{n,N_h-1}\}$. Finally, combining $\{\hat{X}_{n,0}, \cdots, \hat{X}_{n,N_h-1}\}$ with $\hat{Y}_n$ through a parallel-to-serial (P/S) converter, we obtain $\hat{X}_n$, the overall estimate of X_n.

Comparing the receiver design of MDFH with that of the conventional FH scheme, the major cost we pay is more computational complexity. In other words, we are trading for higher spectral efficiency with higher computational complexity. With advances in small size VLSI circuit design, the implementation complexity is not as forbidden to us today as it was two decades ago.

It should be pointed out that with blind frequency detection, the security feature of the conventional FH systems is completely lost since PN hopping can no longer prevent unauthorized interception. On the other hand, if the PN scrambling is applied to the input data stream before transmission, then MDFH will be secure without increasing the complexity at the transmitter end, as the unauthorized user can only receive the encrypted signal.

IV. EXTENSION OF MDFH TO MULTIPLE ACCESS ENVIRONMENT

One major challenge in the current frequency hopping multiple access (FHMA) system is collision. In FHMA systems, multiple users hop their carrier frequencies independently. If two users transmit simultaneously in the same frequency band, a collision, or hit occurs. In this case, the probability of bit error is generally assumed to be 0.5.

If there are N_c available channels and K active users (i.e., $K - 1$ possible interfering users), assuming all N_c channels are equally probable and all users are independent, then the probability that a collision occurs is given by

$$P_h = 1 - (1 - \frac{1}{N_c})^{K-1} \tag{9}$$

$$\approx \frac{K-1}{N_c} \quad \text{when } N_c \text{ is large.} \tag{10}$$

Taking $N_c = 64$ as an example, the relationship between the probability of collision and the number of active users is shown in Fig. 5. The high collision probability severely
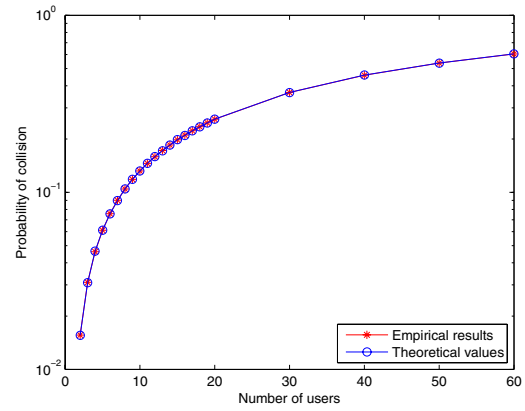

Fig. 5. Probability of collision (P_h) versus the number of users (starting at the 2-user case) for $N_c = 64$.

limits the number of users that can be simultaneously supported by an FH system. Assuming BFSK modulation and $N_h = 1$ for example, the probability of bit error can be modeled as $P_e = \frac{1}{2}e^{-\frac{E_b}{2N_o}}(1 - P_h) + \frac{1}{2}P_h$, where $\frac{E_b}{N_o}$ is the bit level signal-to-noise ratio (SNR).

Our discussions above indicate that an alternative approach is to develop collision-free FHMA techniques. To extend MDFH

to multiple access environment, collision-free scheme is convenient due to the blind frequency detection techniques used at the receiver end. Otherwise, we would have to include a user-ID at each hop for each user, which may reduce the spectral efficiency. In this paper, we choose to incorporate TDMA with the single user MDFH to obtain a TD-MDFH multiple access scheme, as shown in Fig. 6. Each user is periodically assigned
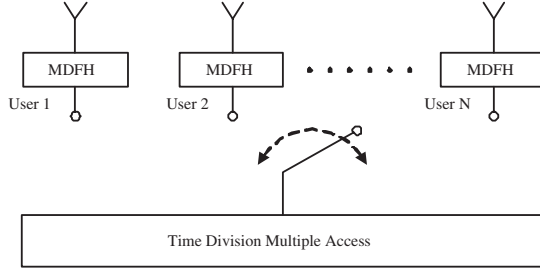

Fig. 6.   The frame structure of the TD-MDFH scheme.

a time slot to transmit his/her information. Each active user transmits to the base station only in its own assigned time slot or slots so that inter-user interference is completely eliminated.

V. QUANTITATIVE PERFORMANCE ANALYSIS

In this section, quantitative analysis with respect to bit-error-rate (BER) and spectral efficiency is carried out for the proposed MDFH scheme.

A. BER Analysis

Recall that the input bit stream is grouped into carrier bits and ordinary bits, where carrier bits are embedded in hopping frequency selection and the ordinary bits are mapped to symbols from a predetermined constellation and then transmitted through selected frequency bands. It is interesting to note that *non-uniformity* exists in the carrier bits and the ordinary bits, in the sense that they have different BER performances.

1) BER of the carrier bits: Based on the receiver design in MDFH, performance analysis of carrier bits is analogous to that of non-coherent FSK demodulation. For non-coherent detection of FSK modulation, if M_F is the size of symbol alphabet, the probability of symbol error is given in [11, eqn. (5-4-46)]

$$P_{s,FSK}\left(\frac{E_b}{N_0}\right) = \sum_{m=1}^{M_F-1}\binom{M_F-1}{m}\frac{(-1)^{m+1}}{m+1}e^{-\frac{m\log_2 M_F}{(m+1)}\frac{E_b}{N_0}},$$
(11)

where $\frac{E_b}{N_0}$ is the average bit level signal-to-noise ratio (SNR). Let $k_F = \log_2 M_F$, then the probability of bit error, $P_{e,FSK}$, can be written as [11],

$$P_{e,FSK}\left(\frac{E_b}{N_0}\right) = \frac{2^{k_F-1}}{2^{k_F}-1}P_{s,MSK}\left(\frac{E_b}{N_0}\right).$$
(12)

For the MDFH scheme, $M_F = N_c$, the total number of channels, and $k_F = B_c$. It should be pointed out that in MDFH, the transmission of the carrier bits does not require any extra signal power other than the transmission of the ordinary bits. Let $\frac{E_b^{(o)}}{N_0}$ denote the bit-level SNR with respect to the ordinary

bits, then the effective SNR for calculating the probability of bit error for the carrier bits is $\frac{E_b^{(c)}}{N_0} = \frac{E_b^{(o)}}{N_0}$.

Recall that in the proposed MDFH scheme, the length of each block is $L = N_h B_c + B_s$, where B_s denotes the number of ordinary bits, and $N_h B_c$ is the number of carrier bits. Taking into consideration that in MDFH, carrier bits do not consume additional transmit power, the average bit level SNR for MDFH is given by $\frac{E_b}{N_0} = \frac{B_s}{N_h B_c + B_s}\frac{E_b^{(o)}}{N_0}$. It then follows that the probability of bit error for the carrier bits in MDFH

$$P_{e,MDFH}^{(c)}\left(\frac{E_b}{N_0}\right)$$
$$= \frac{2^{B_c-1}}{2^{B_c}-1}\sum_{m=1}^{N_c-1}\binom{N_c-1}{m}\frac{(-1)^{m+1}}{m+1}e^{-\frac{km}{(m+1)}\frac{E_b^{(o)}}{N_0}}.$$
(13)

Equivalently, the probability of carrier frequency detection error is

$$P_{s,MDFH}^{(c)}\left(\frac{E_b}{N_0}\right) = \frac{2^{B_c}-1}{2^{B_c-1}}P_{e,MDFH}^{(c)}\left(\frac{E_b}{N_0}\right).$$
(14)

2) BER of the ordinary bits: BER of the ordinary bits is determined by the modulation methods. If FSK is utilized, then the BER can be calculated in a similar manner as that of the carrier bits. In the following, we consider the case of transmitting the ordinary bits through M-ary QAM.

Recall that if $M = 2^{B_s}$ (without loss of generality, assuming B_s is even), the probability of symbol error for the M-ary QAM is [11, eqn. (5-2-78) & (5-2-79)]

$$P_{s,QAM}\left(\frac{E_b}{N_0}\right) = 1-\left(1-2(1-\frac{1}{\sqrt{M}})Q\left(\sqrt{\frac{3\log_2 M}{(M-1)}\frac{E_b}{N_0}}\right)\right)^2,$$
(15)

where $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-\frac{t^2}{2}}\,dt$.

Taking 16-QAM as an example, we have

$$P_{s,16-QAM}\left(\frac{E_b}{N_0}\right) = \frac{9}{4}\left(\frac{4}{3} - Q\left(\sqrt{\frac{4}{5}\frac{E_b}{N_0}}\right)\right)Q\left(\sqrt{\frac{4}{5}\frac{E_b}{N_0}}\right).$$
(16)

Accordingly, the probability of bit error is

$$P_{e,16-QAM}\left(\frac{E_b}{N_0}\right) = \frac{9}{16}\left(\frac{4}{3} - Q\left(\sqrt{\frac{4}{5}\frac{E_b}{N_0}}\right)\right)Q\left(\sqrt{\frac{4}{5}\frac{E_b}{N_0}}\right).$$
(17)

In MDFH, the BER calculation of the ordinary bits, $P_{e,MDFH}^{(o)}$, takes three steps:

i) As in the previous subsection, we should be aware that the average bit level SNR in MDFH is only a fraction of that of the ordinary bits, $\frac{E_b}{N_0} = \frac{B_s}{N_h B_c + B_s}\frac{E_b^{(o)}}{N_0}$.

ii) When the carrier frequency is detected correctly (with probability $\left(1 - P_{s,MDFH}^{(c)}\left(\frac{E_b}{N_0}\right)\right)$), the probability of bit error can be calculated based on the BER of coherently detected M-ary QAM, given by

$$P_{e1} = P_{e,16-QAM}\left(\frac{E_b^{(o)}}{N_0}\right).$$

When the carrier frequency is not correctly detected (with

probability $P_{s,MDFH}^{(c)}\left(\frac{E_b}{N_0}\right)$), it is reasonable to assume that probability of bit error is $P_{e2} = \frac{1}{2}$.

iii) Since each QAM symbol undergoes N_h hops, we first estimate the QAM symbol independently for each hop, then apply bit-wise majority voting for the N_h estimates to make the final decision. Hence, one bit error is caused by at least $\lceil \frac{N_h}{2} \rceil$ unsuccessful recovery in a particular bit location. Taking the effect of the majority voting into consideration, the error probability for ordinary bits is given by (21) & (22) listed at the bottom of this page.

3) Overall BER for MDFH: The overall BER of the MDFH scheme is modeled as the linear combination of $P_{e,MDFH}^{(c)}$ and $P_{e,MDFH}^{(o)}$ based on the number of carrier bits and the number of ordinary bits in each block. According to our discussion above, we have

$$
\begin{aligned}
P_{e,MDFH}\left(\frac{E_b}{N_0}\right) &= \frac{N_h B_c}{N_h B_c + B_s} P_{e,MDFH}^{(c)}\left(\frac{E_b}{N_0}\right) \\
&+ \frac{B_s}{N_h B_c + B_s} P_{e,MDFH}^{(o)}\left(\frac{E_b}{N_0}\right) \quad (18)
\end{aligned}
$$

B. Spectral Efficiency Analysis

We compare the spectral efficiency of the proposed TD-MDFH scheme with that of the conventional FH scheme. Note that for TD-MDFH, there is only one active user at a time. At the same time, the FH systems allow simultaneous transmission from more than one users, but with an error probability heavily influenced by the collision probability. For quantitative analysis, the performance measure adopted here is the average information rate R_b (bits/second) for a given BER level over the same bandwidth, as is widely used for capacity analysis.

We start with the *single user case*, that is, there is only a single user in both systems and no collisions need to be taken into consideration for the conventional FH system. Recall that T_s and T_h denote the symbol period and the hopping duration, respectively. $R_s = 1/T_s$ is then the symbol rate in the conventional FH system, and $N_h = T_s/T_h$ is the number of hops per symbol duration, $N_h \geq 1$. For fair comparison, we assume that both systems has the same T_s, the same hop rate, and use the same constellation with M symbols, i.e., the number of bits per symbol is $B_s = \log_2 M$. In this case, the bit rates for FH and MDFH can be expressed as:

$$
\begin{aligned}
R_{b,FH} &= B_s R_s, & (19) \\
R_{b,MDFH} &= B_s R_s + B_c N_h R_s. & (20)
\end{aligned}
$$

As will be demonstrated in the following example, since in MDFH, transmission of the carrier bits does not require additional signal power, MDFH with rate $R_{b,MDFH}$ delivers better BER performance compared to that of the conventional FH with rate $R_{b,FH}$ under the same SNR level. In other words, since $N_h \geq 1$, we always have $R_{b,MDFH} > R_{b,FH}$, i.e., MDFH is always more efficient than the conventional fast FH scheme.

Example 1   Assume the number of available channels is $N_c = 64$, and 16-QAM modulation is adopted for both MDFH and FH systems. That is, $B_c = 6$ and $B_s = 4$. The BER performance with respect to three different hop rates, i.e., $N_h = 3, 5, 7$, is independently measured for both systems, and the results are provided in Fig. 7. As can be seen, the MDFH system outperforms the FH system with big margins.
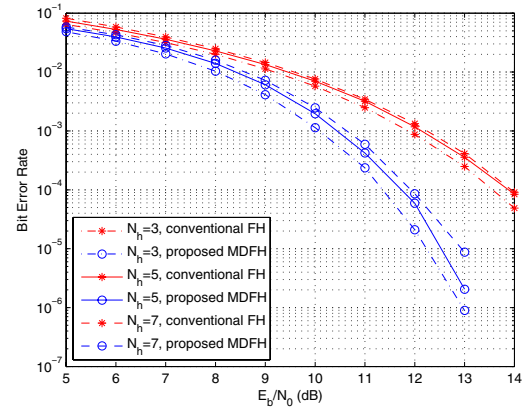

Fig. 7.   BER comparison of conventional FH and the proposed MDFH in the single user case.

We further compare the BER performances of the carrier bits and the ordinary bits in MDFH, as shown in Fig. 8. It can be seen that there is almost a perfect match between the simulation results and the theoretical results derived in (13) & (21). Moreover, it can be observed that the BER of carrier bits is worse than that of ordinary bits, since the same ordinary bits are transmitted via multiple hops, and the BER is therefore substantially improved through majority voting even if certain

$$
P_{e,MDFH}^{(o)}\left(\frac{E_b}{N_0}\right) = \sum_{i=0}^{N_h} \binom{i}{N_h} \left(P_{e,MDFH}^{(c)}\left(\frac{E_b}{N_0}\right)\right)^i \left(1 - P_{e,MDFH}^{(c)}\left(\frac{E_b}{N_0}\right)\right)^{N_h - i} P_e(i), \quad (21)
$$

where $P_e(i)$ is the probability of bit error when i out of N_h carrier frequencies are not correctly detected, given by

$$
P_e(i) = \sum_{j=\lceil \frac{N_h}{2} \rceil}^{N_h} \sum_{k=0}^{j} \binom{k}{N_h - i} (P_{e1})^k (1 - P_{e1})^{N_h - i - k} \binom{j-k}{i} (P_{e2})^{j-k} (1 - P_{e2})^{i-j+k}. \quad (22)
$$

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the ICC 2007 proceedings.

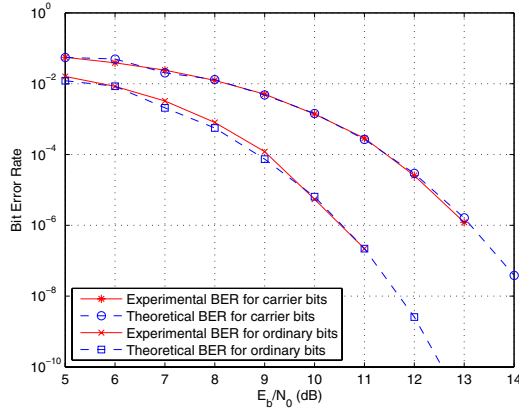carrier frequencies are not correctly detected.

Fig. 8.   BER comparison of the carrier bits and the ordinary bits in MDFH: $N_h = 3$.

Next, we explore the more general case where there are multiple users in both systems. Consider a conventional fast FH system with $N_u(> 1)$ users, each transmitting 2^{B_s}-ary MFSK signals over N_c frequencies. In the case when multiple-access interference is dominant over the background noise, an upper bound on the average bit error rate, $P_{e,FH}^{(u)}$ for random hop pattern has been provided in [3]:

$$ P_{e,FH}^{(u)} = \frac{2^{B_s}}{4}[1 - (1 - \frac{1}{N_c})^{N_u-1}]^{N_h}. \tag{23} $$

It then follows from (23) that

$$ R_{b,FH} = \frac{R_s N_h B_s \ln[1 - (1 - \frac{1}{N_c})^{N_u-1}]}{\ln P_{e,FH}^{(u)} - B_s \ln 2 + \ln 4}. \tag{24} $$

For the proposed MDFH scheme, there is no multiple-access interference so that each user can enjoy exactly the same maximum information bit rate $R_{b,MDFH}$. We need to compare $R_{b,MDFH}$ with $N_u R_{b,FH}$ under the same BER and bandwidth requirements. As it is not easy to derive an explicit expression of R_b in terms of P_e in MDFH, we illustrate the system performance through the following numerical example.

Example 2 Assume $N_c = 64$ (i.e., $B_c = 6$), $N_h = 5$, $B_s = 4$. Consider the transmission over one symbol period. The conventional FH system can support multiple users simultaneously, while the TD-MDFH system can only allow one single user. Assume the required BER is 10^{-5}, from Fig. (9), it can be seen that the conventional fast FH system can only accommodate up to 6 users. Therefore, during one symbol period, the FH system can transmit $N_u B_s = 6 \cdot 4 = 24$ bits. For the TD-MDFH scheme, the BER 10^{-5} can be achieved at $\frac{E_b}{N_O}$ less than 13dB, which is easy to obtain in most practical systems. During one symbol period, the number of total transmitted information bits is $N_h B_c + B_S = 5 \cdot 6 + 4 = 34$, which implies an increase of 41.67% in spectral efficiency.
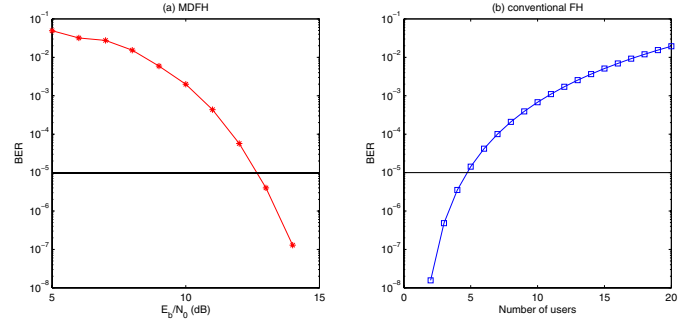

Fig. 9.   Performance comparison of FH and MDFH in the multi-user case: $N_c = 64$, $N_h = 5$, $B_s = 4$.

VI. Conclusion

In this paper, we introduced the concept of message-driven frequency hopping scheme. By embedding part of information into the process of hopping frequency selection, the spectral efficiency of the FH system can be significantly improved. To resolve collisions and enable the simple receiver design in multiple access environment, the TDMA architecture was incorporated with the MDFH transmission to formulate a collision-free multiple access system. Performance analysis was provided to demonstrated the superior bandwidth efficiency of the proposed scheme.

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